

A possible signature of primordial stellar populations in $z = 3$ Lyman α emitters

Akio K. Inoue

*College of General Education, Osaka Sangyo University, 3-1-1, Nakagaito, Daito, Osaka
574-8530, Japan*

Abstract. Observations with Subaru telescope have detected surprisingly strong Lyman continuum (LyC; ~ 900 Å in the rest-frame) from some Lyman α emitters (LAEs) at $z = 3.1$. We have examined the stellar population which simultaneously accounts for the strength of the LyC and the spectral slope of non-ionizing ultraviolet of the LAEs. As a result, we have found that stellar populations with metallicity $Z \geq 1/50 Z_{\odot}$ can explain the observed LyC strength only with a very top-heavy initial mass function (IMF; $\langle m \rangle \sim 50 M_{\odot}$). However, the critical metallicity for such an IMF is expected to be much lower. A very young (~ 1 Myr) and massive ($\sim 100 M_{\odot}$) extremely metal-poor ($Z \leq 5 \times 10^{-4} Z_{\odot}$) or metal-free (so-called Population III) stellar population can also reproduce the observed LyC strength if the mass fraction of such ‘primordial’ stellar population is $\sim 1\%$ in total stellar mass of the LAEs.

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INTRODUCTION

The first generation of stars in the Universe is the stellar population without any metal elements. Although the formation of such metal-free stars, or so-called Population III (Pop III) stars may last until $z \sim 2-3$ if the metal enrichment in the intergalactic medium (IGM) is inefficient, there is no firm observational evidence of the stellar population.

The stellar population with metallicity $Z < 10^{-5}$, which is $< 1/2000 Z_{\odot}$, is classified as extremely metal-poor (EMP) stars. Low-mass EMP stars found in the halo of the Galaxy are survivors of the early stage of the formation of the Galaxy. On the other hand, it is expected that their high-mass counterpart existed in the early days and died out until the current epoch. Yet, there is no direct observational evidence of such massive EMP stars at high- z .

This paper presents a possible signature of such ‘primordial’ stellar populations in high- z galaxies. There is a new population of galaxies at $z \sim 3$ detected in their rest-frame ~ 900 Å, Lyman continuum (LyC). Surprisingly strong LyC relative to non-ionizing ultra-violet (UV) was reported by [6]. This may indicate the presence of the primordial stellar populations as shown in [1, 5] and below.

REST UV TWO-COLOUR DIAGRAM

[6] and [5] have found extremely strong LyC from some Lyman α emitters (LAEs) at $z = 3.1$. Their redshifts were confirmed with spectroscopy. However, some LAEs show

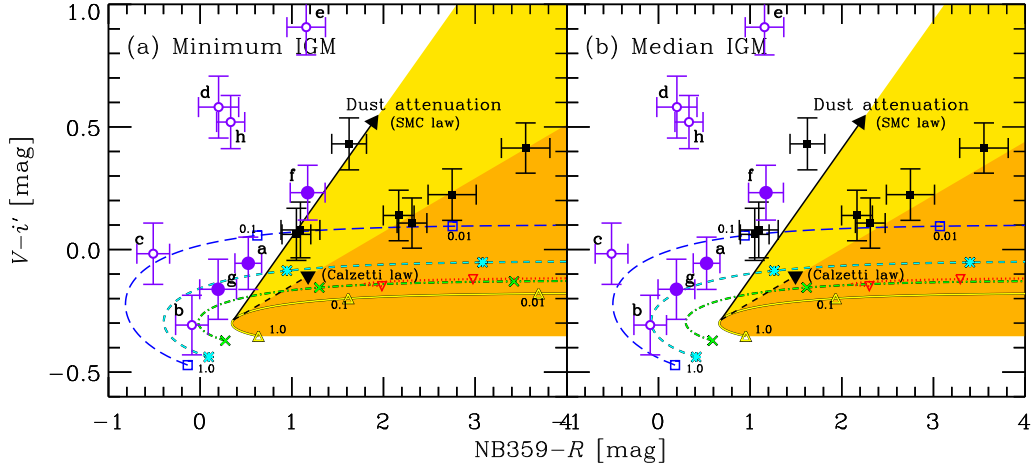


FIGURE 1. Rest UV two-colour diagram for $z \simeq 3.1$ LyC emitting galaxies. The vertical axis, $V - i'$, indicates non-ionizing UV spectral slope, and the horizontal axis, $NB359 - R$, indicates LyC-to-UV flux density ratio. The filled circles with errorbars are the 3 LAEs without $\text{Ly}\alpha$ line offset [5] and the open circles with errorbars are the 5 LAEs with the line offset [5]. The filled squares with errorbars are LBGs reported in [6]. The colours expected from the SED model with escaping stellar and nebular emissions developed by [1] are shown by the dotted curve with inverse triangles (model Ac in Table 1), the solid curve with triangles (model A), the dot-dashed curve with x-marks (model B), the short-dashed curve with asterisks (model C), and the long-dashed curve with squares (model D). These curves are a function of f_{esc} and the colours for $f_{\text{esc}} = 1.0, 0.1$, and 0.01 are indicated by the symbols. We have assumed minimum and median IGM attenuations in panels (a) and (b), respectively, based on [4, 5]. The two diagonal arrows show dust attenuations with $E(B - V) = 0.1$ for the SMC law (solid arrow) and the Calzetti law (dashed arrow). The shaded regions indicate the regions explained by the stellar population model A with a combination of IGM and dust attenuations.

TABLE 1. Stellar population models.

Model	Z/Z_{\odot}	IMF	SF history	age	SED reference
Ac	1/5	Salpeter	Constant	100 Myr	STARBURST99 (v.5.1)
A	1/50	Salpeter	Instantaneous	1 Myr	STARBURST99 (v.5.1)
B	1/50	Top-heavy	Instantaneous	1 Myr	STARBURST99 (v.5.1)
C	1/2000	Massive	Instantaneous	1 Myr	Schaerer (2003)
D	0	Massive	Instantaneous	1 Myr	Schaerer (2003)

a spatial offset between $\text{Ly}\alpha$ emission line and LyC. These objects may have a faint foreground galaxy accounting for the ‘pseud-LyC’. However, it is difficult to attribute all the objects to foreground contamination in a statistical sense because of the smallness of the offset ($< 1''$) [5]. Figure 1 shows the extreme strength of the LyC of the LAEs found by [6, 5]. The filled circles are the most reliable objects without any offset, while the open circles are the objects with the small offset. The filled squares are the sample of Lyman break galaxies of [6].

Single stellar population model

Let us compare the observed colours with a spectral model with a single stellar population. In particular, we allow an escape of nebular LyC (bound-free recombination continuum) as well as an escape of stellar LyC as described in [1]. This escaping nebular LyC boosts the flux just below the Lyman limit. We call it ‘Lyman limit bump’ [1]. Actually, the NB359 filter used in observations of [6] exactly traces the Lyman limit bump at $z = 3.1$. Then, the NB359– R colour becomes bluest not when the LyC escape fraction $f_{\text{esc}} = 0$ but when $f_{\text{esc}} \approx 0.5$. This results in a round shape of the model curves in Figure 1 which are a function of f_{esc} . Among 5 types of the stellar populations in Table 1, we find that the stellar populations with an ordinary sub-solar metallicity and with a Salpeter IMF (i.e. models A and Ac) do not fit the observed LAEs. If we insist on an ordinary metallicity, the IMF should be massive (models B). However, such a massive IMF is expected only at extremely low metallicity like $Z < 10^{-(3-6)} Z_{\odot}$ [7]. If we wish to explain the LAEs bluest in NB359– R , some but not all of which may be foreground contamination, a stellar population with massive EMP or metal-free (models C or D) is required.

Two stellar population model

The previous subsection shows that the LAEs detected in LyC by [6] are likely to contain a primordial stellar population such as massive Pop III or EMP stars. But how much amount of these exotic stars are required in them? To discuss these questions, let us consider a system in which a primordial stellar population and a normal stellar population with sub-solar metallicity and Salpeter IMF coexist. We assume that the normal population makes stars with a constant rate; the model Ac in Table 1. For the primordial population, we adopt the model D (Pop III). The mass fraction of the primordial population in the total stellar mass is a parameter for the mixture. The normal population may exist in dusty environment, but the primordial population are likely to be dust-free. A result is shown in Figure 2.

The LAEs without offset (objects **a**, **f** and **g**; filled circles in Fig. 2) require a primordial mass fraction of 0.1–10%. The bluest LAEs (objects **b** and **c**; open circles) require a primordial mass fraction of more than 10%, but we could not reject the possibility that their NB359 flux was foreground contamination individually [5]. The LAEs which are red in $V - i'$ (objects **d**, **e** and **h**; open circles) can be explained by a model with the SMC law and a small amount of attenuation as $E(B - V) \simeq 0.2\text{--}0.3$ and with a primordial mass fraction of a few 0.1%. Note that the possibility of foreground contamination, especially for **d** and **e**, is the largest because of the largest line offset [5].

SUMMARY AND FUTURE PROSPECTS

We have suggested that the extreme strength of LyC observed in some LAEs at $z = 3.1$ indicates the presence of massive EMP or Pop III stars in them. Such a galaxy population could be a cosmic ‘ionizer’ for the reionization at $z > 6$. Indeed, there seems an evolution

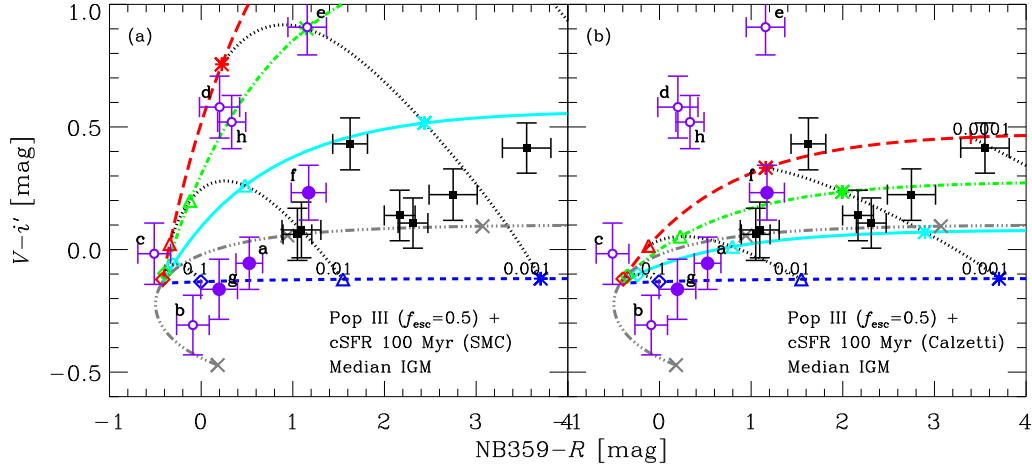


FIGURE 2. Same as Fig. 1 but comparisons with two stellar population models: the underlying normal stellar population (model Ac in Table 1) and the additional Pop III stars (model D). The SMC dust extinction law is assumed for the panel (a) but the Calzetti attenuation law is assumed for (b). The median IGM attenuation is assumed for both panels. The short-dashed curves are the sequences of the colour as a function of the mass fraction of Pop III stars for dust-free underlying stellar population. The solid, dot-dashed, and long-dashed curves are the same sequences but for dusty underlying population with $E(B - V) = 0.1, 0.2$, and 0.3 , respectively. Note that the Pop III stars are assumed to be always dust-free. The positions for the mass fraction of $0.1, 0.01, 0.001$, and 0.0001 are indicated by dotted curves with diamonds, triangles, asterisks, and plus-mark, respectively. For Pop III stars, the contribution of escaping nebular LyC is taken into account, assuming $f_{\text{esc}} = 0.5$. The colour sequence with other f_{esc} is shown by the triple-dot-dashed curve as in Fig. 1. For the underlying population, $f_{\text{esc}} = 0.01$ is assumed.

of LyC emissivity of galaxies toward high- z [3]. This may be caused by an increase of this type of the galaxy population at high- z . In future, we should confirm the presence of the primordial stellar population in the galaxies. For example, we can constrain the metallicity to be $Z < 10^{-3} Z_{\odot}$ if the ratio of $[\text{OIII}] \lambda 5007$ to $\text{H}\beta$ is less than 0.1 [2]. Deep near-infrared spectroscopy for the LAEs is strongly encouraged.

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